Technical Note 1965-62

E. Gehrels

A Review of Long-Range Earth Strain Measurement Techniques for Providing Earthquake Warning

13 December 1965

Prepared for the Advanced Research Projects Agency
under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

ESRL

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. This research is a part of Project Vela Uniform, which is sponsored by the U. S. Advanced Research Projects Agency of the Department of Defense; it is supported by ARPA under Air Force Contract AF 19(628)-5167 (ARPA Order 512).

142

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

A REVIEW OF LONG-RANGE EARTH STRAIN MEASUREMENT TECHNIQUES FOR PROVIDING EARTHQUAKE WARNING

E. GEHRELS

Group 64

TECHNICAL NOTE 1965-62

13 DECEMBER 1965

LEXINGTON MASSACHUSETTS

ABSTRACT

One of the most valuable tools for studying earthquakes and faults is earth strain or displacement measurements. Geologists are now looking for minute telltale displacements that might occur before an earthquake. This report discusses the possible accuracies that might be achieved by three different electromagnetic measurement techniques: 1) Microwave phase measurements, 2) Modulated light beams, and 3) Laser interferometers. The first is extremely sensitive to propagation errors. The second can achieve a modest degree of accuracy, 10^{-7} or better, and will clearly meet the minimum requirements. The third will provide by far the greatest degree of accuracy for propagation path lengths over which at least a partial degree of coherence of the wave front can be maintained.

Accepted for the Air Force
Stanley J. Wisniewski
Lt Colonel, USAF
Chief, Lincoln Laboratory Office

A REVIEW OF LONG-RANGE EARTH STRAIN MEASUREMENT TECHNIQUES FOR PROVIDING EARTHQUAKE WARNING

I. INTRODUCTION

A study has been under way by a national ad hoc committee under the direction of Dr. Frank Press. The initial results of this study are written up in a report[1] which summarizes the current state of thinking about the possibilities of earthquake prediction.

Up until the present time, no success has been achieved by anyone in predicting an earthquake. The cause or triggering mechanism for an earthquake still remains unknown. It is known that the earth undergoes long term movements which develop stresses that increase with time. A point is reached at which the rock can no longer sustain these forces; the sudden release of the stored elastic energy is an earthquake.

The Press Committee report recommends a study of the nature of materials under extreme pressures in the hope of finding out why an earthquake takes place exactly when it does. However, the major emphasis is on the continuous monitoring of numerous variables which might be expected to show subtle or marked changes before an earthquake. A list of some of these variables and the anticipated accuracies to which they might be measured is tabulated below:

Phenomenon	Accuracy (near state-of-the art)	Comments
Gravity	10^{-7} g absolute 10^{-9} g changes	
Tilt	10^{-9} radians	Has been successful in predicting volcanic erruptions.

Phenomenon	Accuracy (near state-of-the art)	Comments
Magnetic Field	.1 gamma	One observer has claimed to have noticed a variation prior to the Alaska Good Friday quake.
Microseismic Activity	1 Å — 10 Å displacement	There have been claims of such observations preceding certain quakes. However, in many carefully observed quakes there was no such activity.
Short Range Earth Strain 100 ft. quartz rod strainmeters[2]	10^{-9} changes 10^{-7} instrumental drifts 10^{-6} noise from local rock strains	Fairly recent technique. Has not yet yielded premonitory signs of an earthquake.
Long Range Earth Strain Long base line (1-10 km) laser interferometer strain meter	10^{-9} in enclosed tube 10^{-7} in open atmosphere	Has never been constructed.*

This report will be confined to long base-line (1 — 10 km) strain measurements made by electromagnetic means. In addition to the laser interferometer referred to in the Press report, microwave phase measurements and the use of modulated light beams will be discussed.

In all three instances, the object is the precision measurement of the distances between pairs of reference points in the bedrock on either side of a fault. This is an extension of the long-term survey measurements that have been made in fault regions. From such measurements, long-term (secular) strain

---

*Short-length laser earth strain meters have been built.[3] These, however, are more nearly comparable to the quartz rod strain meter. The one described in the above reference is 10 meters long and is compared only against a pendulum seismograph.

build-ups have been observed during the periods between earthquakes. The measurements are rough, and, as far as one can tell, the build-up is linear with time. The rate of build-up is correlated with the frequency of earthquake activity (Japan 1×10^{-5}/yr., California 1×10^{-6}/yr., and New Jersey 2×10^{-7}/yr.), but no relation is known between the magnitude of the accumulated strain and the time that an earthquake occurs. The hope is that after the secular strains and other strains of known periodicity, e.g., the semi-diurnal earth tides (amplitude 10^{-8}) are taken into account, movements associated with an impending earthquake, e.g., plastic flow of underlying rocks, might become observable. By drastically improving the accuracy of the measurement, short-term effects should be observable. The three techniques will be discussed in the order of increasing sophistication: 1) Microwave phase measurements, 2) Modulated light beam, and 3) Laser interferometer.[4]

II. MICROWAVE PHASE MEASUREMENTS

There exists a commercial instrument, called the Tellurometer, which has a claimed <u>instrumental</u> accuracy of 2 cm over a distance of 30 km (6 parts in 10^7). It was with the object of ascertaining whether this accuracy could be substantially improved that this part of the study was made. From the standpoint of electronic instrumentation, the answer is definitely yes.

In essence, the principle of the Tellurometer can be described as follows. A continuous wave carrier at 10,000 mc/s (3 cm wavelength) is transmitted from point A. This signal is received at point B, from which another signal shifted up in frequency by a small, but precisely known frequency difference is transmitted back to A. At A this received signal is down-converted by precisely the same amount. The phase of this down-converted

signal is the same (with some very minor corrections) as the phase that would have been received had it been possible to re-transmit from B the same frequency as received from A. The phase difference between the outgoing signal and the received (down-converted) signal is simply the round trip phase delay.* Thus, even with a crude phase measurement, e.g., 6° accuracy, a measurement can be made to $\frac{1}{50}\lambda$, or better than a part in 10^8.

In reality, measurements to this accuracy are not meaningful with this instrument. Ground reflections can cause signals that are almost as strong as the desired signal, but that arrive via longer paths. The effect is not systematic and predictable; it can cause either a positive or a negative error depending upon the phase relationship of the direct and the reflected signal. Since it is generally quite impractical to make sufficiently directive microwave antennas to discriminate against the ground reflection, the best approach is to try to average out the effect by selecting a number of frequencies in the hope that the positive errors will average out against the negative ones.

A still more fundamental limitation, and one that will have to be considered with all the electromagnetic techniques, is atmospheric refraction. The dry atmosphere at sea level has a refracted index of 1.0003, that is, its index differs from unity by about 300 parts per million (300 N units). If it

---

*A phase measurement at a single frequency does not tell the number of wavelengths, but only the fractional part of the wavelength. 30 km (one way) corresponds to 2×10^6 wavelengths round trip. A phase measurement of zero gives no indication of whether the distance was actually 0, 1,000,000 λ, or 2,000,001 λ, etc. It is possible to distinguish between the first two possibilities, and to obtain a coarse measurement of distance by repeating the phase measurement at a frequency higher by 1 part in 10^7. Zero distance would still give zero phase. 30 km would be 2,000,000.2 wavelengths, giving a phase angle of 72°. This procedure can be repeated with successively greater frequency increments until all the ambiguities have been removed.

were not taken into account, any distance measurement would be higher by about 300 parts per million. Of course, it is possible to correct for a major part of this refraction. The International Union of Geodesy and Geophysics [1960] standardized on the following formula for calculating refractive index

$$n = 1 + [\frac{103.49}{T} (P - e) + \frac{86.26}{T} (1 + \frac{5748}{T}) e] 10^{-6},$$

where

T is the temperature in degrees Kelvin,

P is the pressure in millimeters of mercury,

e is the partial pressure of water vapor in millimeters of mercury.

The refraction contributed by the dry air is just linearly dependent upon the density. However, the water vapor contributes a large effect highly out of proportion to its concentration on account of its polarizability at microwave frequencies. Fully 25% of the refraction can be contributed by the water vapor.

The accuracy of the refractive index corrections depends upon which of the atmospheric parameters can be measured over the whole path. Generally, this is not possible; it is practical to obtain temperature, pressure, and humidity measurements at the terminal stations and perhaps a few intermediate points. As a result, measurements to a few parts in 10^6 are the best that can be achieved in practice at microwave frequencies.*

---

*A method of obtaining an independent measure of the atmospheric refraction by making measurements at two frequencies will be described in the next section for optical measurements. This has been attempted at microwave frequencies by John Sullivan of the MITRE Corporation.[5] However, the small amount of dispersion available at microwaves does not make the method very satisfactory for our purposes.

III. MODULATED LIGHT BEAM

I would now like to discuss another technique -- the modulated light beam. The modulated light beam is at present the most accurate surveying technique. This technique is embodied in a commercial instrument called the Geodimeter. Figure 1 shows its configuration schematically. In essence, a light beam from either an incandescent lamp or a high pressure mercury vapor discharge tube is passed through a Kerr cell, thence through telescope optics to a distant corner reflector type mirror, and then back through another set of optics into a photocell. The Kerr cell modulates the light beam at a rate of about 15 megacycles per second. The phase of this 15 megacycle modulation observed on the photocell is compared with the phase of the outgoing light, giving a measurement of the distance to the reflecting mirror.

A brief description of the Kerr cell is in order since this is really the heart of the system, and I would say, the limitation in the present Geodimeters. A Kerr cell is a small chamber filled with nitrobenzene solution. Nitrobenzene has the property that when an electric field is applied, it becomes birefringent, and if polarized light is passed through this nitrobenzene under these conditions, its plane of polarization is shifted. Thus, if one polarizes the incoming light before the Kerr cell with, for instance, a Nicol prism and places another Nicol prism after the Kerr cell, the rotation of polarization will cause the intensity of the light coming out of the second Nicol prism to change in intensity. Achieving this rotation of polarization in the Kerr cell requires fairly strong electric fields. Typically, a pair of electrodes spaced a millimeter or so requires an applied e.m.f. of about 3000 volts d.c. for biasing plus 3000 volts r.f. at 15 megacycles/sec. supplied from a rather typical

type radio transmitter circuit. The phase of the returned signal can be measured to about one 3600^{th} of a wavelength, that is, about a tenth of a degree, which, for a 15 megacycle frequency, is about 3 millimeters of accuracy. This is, of course, just the instrumental error and is about the limit of what has been achieved with Geodimeters.

Again, as before, we have atmospheric refraction, the ever-present bugaboo. Fortunately, to start out with, the atmospheric refractive effect is not as unpredictable because at optical wavelengths, water vapor behaves in a manner much more similar to that of the air. Actually this refraction is a slight bit less than the air, rather than being twelve times as great. Now, if one could get the average temperature over the whole ray path accurate to within about a tenth of a degree centigrade, one could calibrate the atmospheric refractive effects down to one part in 10^7.*

Recent efforts to correct atmospheric refraction have made use of the dispersion or the difference in the refraction of the air to different wavelengths of light. The techniques are the same as those used in radio phase measurements.[5] For instance, a blue filter may be placed over the Geodimeter and the amount of phase delay observed. Then one may replace this with a red filter. The atmospheric delays in this case will differ by 2%, a much more tractable figure than the amount of delay difference in the case of microwaves (which even with the most favorable choice of frequencies gives only one part

---

*Obviously, barometric pressure and water vapor content are also relevant variables. Large gradients in barometric pressure cannot be sustained (tornadoes and possibly thunder squalls constitute an exception), and consequently the measurement of the pressure at the two terminals provides an excellent measure of the average over the path length. An error of .1 millibar in water vapor partial pressure (an error in the relative humidity of 4% at 20°C) causes less than 3 parts in 10^8 error in the measurement of distance.

in 3000 or .03%). One can even go further if one wants. For instance, one may use 11,000 angstroms and 3000 angstroms, the first figure being chosen because it is a strong line in the neon emission spectrum and 3000 angstroms being chosen because it represents about the limit of short wavelengths before atmospheric absorption becomes excessive. Thus one can achieve a difference of 6% in the refraction air offers. I shall in the subsequent discussion take a compromise figure of 3% and give some numbers for kinds of measurements that can be made in a refractive atmosphere.

Specifically, if we take a base line of ten kilometers, or 10^7 millimeters, the total atmospheric delay is 3000 millimeters. The difference in the atmospheric delay or dispersive delay (the difference in the apparent path lengths for the two colors of light) is 3% of the total refraction or one-hundred millimeters. Now, if we want to reduce the atmospheric refraction error by 3000, we must measure the amount of atmosphere to one part in 3000. Thus, we must measure the dispersive delay to one part in 3000 or $1/30^{th}$ of a millimeter.

This $1/30^{th}$ millimeter is beyond the instrumental accuracies of the existing Geodimeters and hence it would appear that one part in 10^7 is unattainable. However, the Geodimeter was developed several years ago before some of the modern semiconductor techniques were available. In particular, the frequency of 15 megacycles represents a practical limit for the Kerr cell; it is hard to achieve 3000 volts at a much higher frequency across such closely spaced electrodes. The nitrobenzene solution is a poor dielectric, and at a higher frequency 3000 volts would generate a greater amount of heat. Cooling at even 15 megacycles is a distinct problem with the Kerr cell. However,

some of the semiconductor crystals being used today can modulate at 100 megacycles or even a thousand megacycles with 50 to 100 volts applied across them.[6] At Lincoln Laboratory a number of experiments have been performed in which a light beam is modulated at 1000 megacycles. Using a frequency which is thus 60 times as high, the same degree of phase measurement accuracy results in an instrumental error which is $1/60^{th}$ as great in distance. An error of a tenth of a degree in electrical phase measurement at 1000 megacycles corresponds to a round trip distance of .05 millimeters, which is just about accurate enough. I should add that the other necessary techniques such as photocells at 1000 megacycles and 0.1 degree phase measurements at these frequencies have all been well developed and are used regularly at this Laboratory.

There are several other factors which turn out not to be crucial but which do deserve mentioning. One is the water vapor. The water vapor fortunately does have a refraction characteristic versus wavelength in the optical region that is fairly similar to that of air. So, to a first order, its presence does not invalidate this correction procedure. A rough measurement of the water vapor content from standard meteorological reports is sufficient to correct for any minor differences in the dispersion caused by the water vapor present. An effect that one might think would be important, but turns out not to be serious, is the fact that the light takes a curved and therefore longer path than the direct path between two points. Over a ten kilometer path under normal atmospheric conditions, this factor turns out to be only one part in 10^7 in its total effect. Thus, even by using nominal atmospheric refraction profiles, or better yet, profiles obtained from local meteorological reports, one can correct this to sufficient accuracy.

The last problem that I shall refer to in connection with the Geodimeter, and, incidentally, one that is common to all electromagentic measuring techniques, is the problem of resolving ambiguity. The solution can be the same as was described for measurements with the Tellurometer. In this case, however, it is the modulating frequency rather than the frequency of the light itself that is shifted. With the approach I am going to describe next, the direct optical interferometer using lasers, this ambiguity in the number of wavelengths is even more crucial.

IV. LASER INTERFEROMETER

An optical interferometer that actually uses as its yardstick the wavelength of visible light rather than the wavelength of microwaves or wavelengths of relatively low frequency modulation on a light beam is very attractive. It is potentially capable of much greater accuracy than the other techniques. Furthermore, it is in principle quite simple. A laser interferometer is shown schematically in Fig. 2. The laser shines a beam of light through a 45° half-silvered mirror to a distant corner reflector mirror. The corner reflector mirror reflects the light back to another optical system consisting of a telescope, a photocell, and another 45° mirror. The light goes via the two alternate paths; one from the laser to the distant reflector and back, and secondly, the path from the laser to the local 45° mirror to the second mirror a few centimeters away and back to the telescope. If the difference in the optical length of these two paths is a whole number of wavelengths, the two light waves will reinforce. If, however, the two optical paths differ by any odd number of half wavelengths, one will get cancellation. If the mirrors are not exactly lined up or if the beam is not perfectly collimated (either

intentionally or accidentally), there are alternate areas of reinforcement and cancellation, called fringes.

This interferometric technique has been used quite frequently in physical experiments and in standardizing our units of length measure. However, until the advent of the laser, it was only practical over relatively short distances, such as a couple of meters. With conventional spectral sources the problem in using longer distances is the line width of the radiation. Let us assume we want to measure a distance of 10 kilometers, or, in microns, 10^{10} microns, with light that is 1 micron in wavelength. The 10 kilometer path corresponds to a round trip distance of 20 kilometers or 2×10^{10} wavelengths. Now if the light source is not a pure single wavelength, but consists of various components differing by as much as a part in 10^{10}, then for one of the components, the path might be 2×10^{10} wavelengths exactly. For another component, it might be 2×10^{10} plus one-half wavelength. For the first component, one would get reinforcement, or a bright part of the fringe, while simultaneously for the second frequency component from the light source, one would get cancellation. In effect, the fringe would be completely blurred out and the fringe structure would be destroyed. Lasers can achieve frequency stabilities of 100 cycles/second out of a frequency corresponding to 3×10^{14} cycles (1 micron in wavelength). This corresponds to a frequency accuracy of 3 parts in 10^{13}, a blurring as a result of the lasers' line width equal to $1/300^{th}$ of a fringe. This is quite adequate for our purposes. The laser actually could be used to measure to the nearest wavelength over a distance of several hundred kilometers before the line width of the laser would be a real problem.

Another and perhaps more familiar characteristic relevant to these measurements is the absolute frequency accuracy or stability of the laser. The laser itself, although it transmits this very narrow fine line, has a frequency determined most sharply by the cavity, which is in turn determined by the spacing of the mirrors in the resonator. The actual line width of the electron transitions is a few parts in 10^6 and by appropriate selection of the cavity, one can get a laser to operate any place in this range. A simple laser at best has errors of a few parts in 10^6. Concerned with this problem, K. Shimoda and A. Javan[7] of M.I.T. have demonstrated a technique for finding the true center of the laser emission line to 5 parts in 10^{10}, achieving an absolute frequency accuracy to this degree. The technique consists essentially of servoing a cavity to the center of the laser line, thus reducing the absolute frequency instability to well within acceptable limits.

From what I have said so far it is clear that a laser is a natural for achieving extremely highly accurate measurements of distance, and if one were performing measurements in a vacuum, or, as mentioned earlier in this paper, in a tube with a controlled atmosphere of nitrogen, we could end the paper right here with a very optimistic note. However, if one is interested in making long-distance measurements within a reasonable budget, one must contend with the atmosphere. Here all the problems in atmospheric refraction referred to before apply, but with one addition. Before, we had to push the instrumental accuracies to the limit to achieve a meaningful measurement of the atmospheric dispersion, and hence a meaningful calibration of the atmospheric refraction. With the laser the instrumental accuracies are reduced to a few parts in 10^{10}, or a few microns, but the atmosphere does introduce one kind of problem in the

laser interferometer measurements that it does not introduce in the Geodimeter or microwave ranging type measurement, namely, coherence.

The lack of coherence is the same effect that causes stars to twinkle. If the light were to follow just one path, the atmospheric refraction effects or the presence of irregularities would have essentially the same effect for interferometer type devices as it would for the Geodimeter. The phase path and therefore the phase itself would be an erroneous value and would be a value that might fluctuate with time. The phase, however, could be averaged since the irregularities have a bandwidth on the order of 100 cycles/second. A short averaging period would provide a very accurate and reasonable average for the phase. However, in reality, the light does not travel in a single path even in a vacuum or in a uniform atmosphere. This can be demonstrated if one takes a barrier or an opaque rod and inserts it in this path. One will find that the light does not suddenly diminish to zero as the road crosses this geometrical path, but instead occults gradually over a region. This region in which it occults is commonly called the first Fresnel zone and represents the region over which diffraction takes place around the rod. This first Fresnel zone corresponds to the region shown in Fig. 3 where the path around the obstacle, i.e., the alternate path and most direct path differ in length by a half wavelength.

The signal or light intensity at the receiving end is a weighted average of the light transmitted through this whole region. For a wavelength of 1 micron and a path length of 10 kilometers, the diameter of this first Fresnel zone reaches a maximum of about 10 centimeters. If in adjacent areas within this 10 centimeter region the total line integral of the atmospheric refraction

causes phase differences for the alternate paths exceeding a half wavelength, then alternate destructive and constructive interferences will occur. This is the cause of the well-known twinkling effect in stars. The phase will go through angles exceeding 360° and the combination of amplitude and phase scintillation makes it very difficult if not impossible to make meaningful phase averages. This can be seen if one imagines the phase and amplitude plotted on a polar plot. One can imagine the phase averaging procedure as a procedure of watching this phasor vector and taking an average of the phase. It is necessary to follow this phasor vector continuously because, obviously, an electrical phase has an ambiguity of 360°, and following this phasor vector is necessary to determine whether the phase corresponds to, for instance, 40° or 400°, which appear the same. In this incoherent situation, however, the amplitude is repeatedly fading. For example, the phase vector might have successive values 20°, 40°, 100°, 200°, 250°, fade out and then suddenly come back in 180° out of phase. Is this now $250^{\circ} - 180^{\circ}$, namely 70°, or is it 250° + 180°, that is, 430°?

Using the best available quantitative figures on atmospheric refraction, this lack of coherence does not appear to be important over path lengths of 1 kilometer. At about 10 kilometers it appears to reach considerable importance. This does appear to coincide with common experience in observing point light sources over a distance of 1 kilometer; they don't appear to twinkle, yet over a distance of 10 kilometers, there is a distinct twinkling. If the wavefront is completely incoherent, which is manifested by a complete Rayleigh distribution in the amplitude, then it is not possible to make a meaningful measurement of phase. If the wavefront is partially coherent, and this appears to be likely

for 10 kilometers, then it should be possible to recover the phase, although the simple averaging described would not be adequate. Possible techniques in this realm deserve further study because, if it is possible to use this interferometer, the instrumentation is basically more straightforward and simple and the accuracy achievable should be all that is required for the earth strain measurement problem. One will again be back to the point where it is the earth rather than the instrument or even the atmosphere that is limiting our accuracy.

V. CONCLUSIONS

Three possible techniques have been discussed for the accurate measurement of the relative strain in the earth over long base lines. All of these have been employed previously in less exacting applications. The first, microwave ranging, has been the object of extensive development over a period of years. The accuracy figures presently achieved represent fundamental propagation limitations rather than limitations that are amenable to system design improvements. The claimed accuracy of 2 parts in 10^6 for the Tellurometer probably represents nearly the best that can be achieved in this way.

The modulated light beam or Geodimeter with certain important modifications which are now state-of-the-art will provide distance measurement accuracies of 10^{-7}, the minimum accuracy specified in the Press Committee Report. This is a safe, conservative estimate even after taking into consideration the atmospheric refraction and the necessity for accurate dispersion measurements. This report has been conservative in its equipment design considerations in, for instance, using values of accuracies for phase measurements available in commercial off-the-shelf equipment and in assuming a 1000 Mc/sec modulating frequency, whereas in the laboratory, modulating frequencies ten times as high

have been demonstrated.[8] Thus, another order of magnitude in accuracy might be achieved.

Comparison of the above with the laser interferometer is difficult because with the latter, accuracy is not a question. Accuracies of 10^{-9} can be achieved if the system can be made to work at all. An unambiguous phase measurement with an error less than 360° will result in an accuracy limited only by the instability of the laser. If, however, a partial degree of coherence cannot be achieved, no measurement can be made at all.

No difficulty should exist if one is willing to construct a closed tube for the light path (a practical proposition for base lengths up to 1 km, but perhaps not very practical financially for 10 km base lines). If it is seriously desired to achieve an accuracy of 10^{-9} over 10 kms, possibilities for achieving coherence through the open atmosphere should be sought further.

REFERENCES

1. Ad Hoc Panel on Earthquake Prediction--Dr. Frank Press, Chairman, "Earthquake Prediction--A Proposal for a Ten Year Program of Research," May 1965.

2. Hugh Benioff, "Fused-Quartz Extensometer for Secular, Tidal, and Seismic Strains," Bulletin of the Geological Society of America 70, 1019 (1959).

3. V. Vali, R. S. Krogstad, and R. W. Moss, "Laser Interferometer for Earth Strain Measurements," Rev. Scientific Instruments 36, No. 9, 1352 (1965).

4. "Studying the San Andreas Fault," Engineering and Science 28, No. 2, 12 (1964).

5. J. Sullivan and D-82 Staff, "Line Integral Refractometer," MITRE Corp. Special Report SR-112, August 1964.

6. C. J. Peters, "Gigacycle-Bandwidth Coherent-Light Traveling-Wave Amplitude Modulator," Proc. IEEE 53, No. 5, 455 (1965).

7. K. Shimoda and A. Javan, "Stabilization of the N_e-H_e Maser on the Atomic Line Center," Journal Applied Physics 36, 3, Pt. 1, 718 (1965).

8. B. S. Goldstein, R. M. Weigand, "X-Band Modulation of Ga-As Laser," Proc. IEEE 53, No. 2, 195 (1965).

3-64-4258

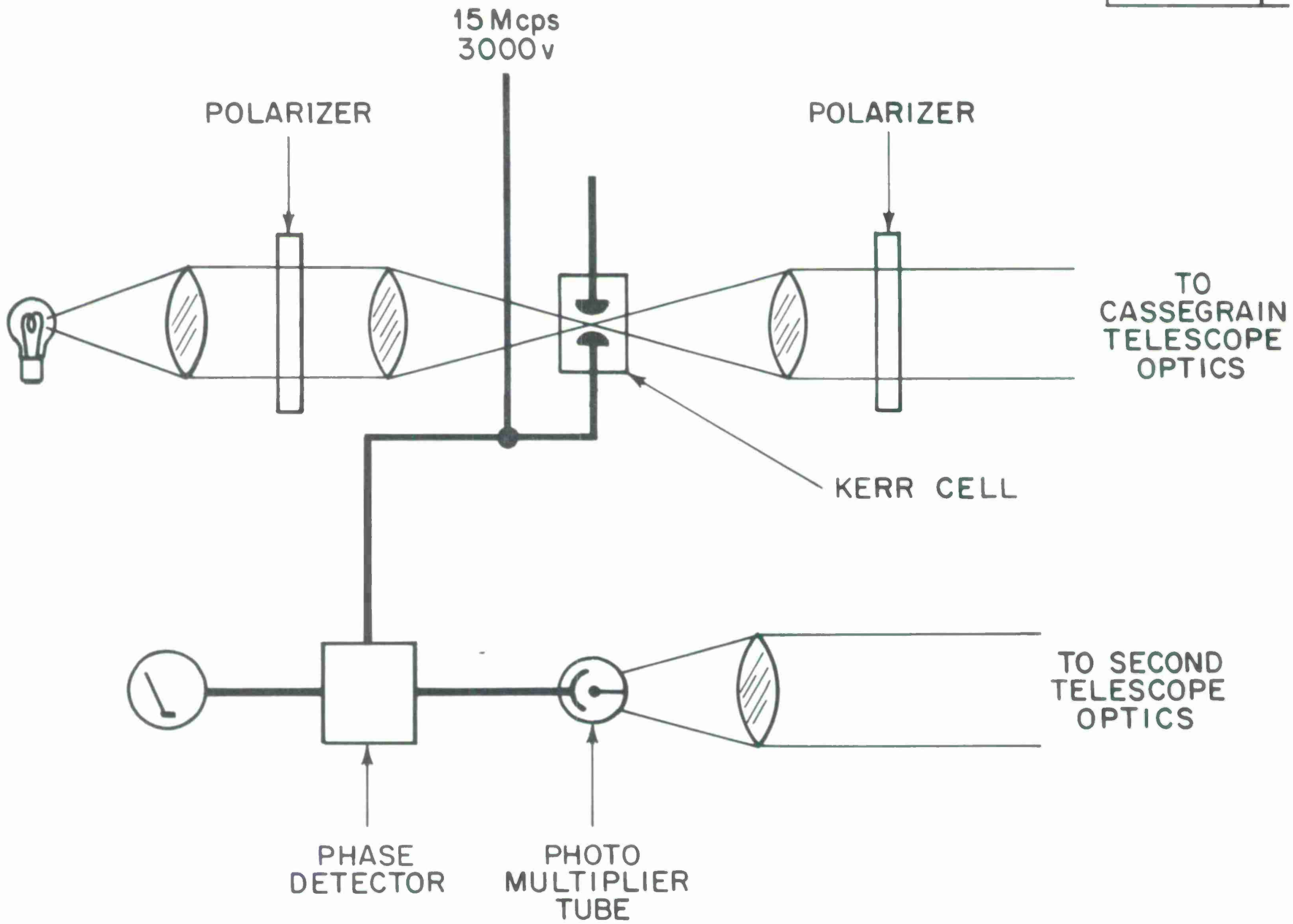


Fig. 1. Schematic diagram of geodimeter optics.

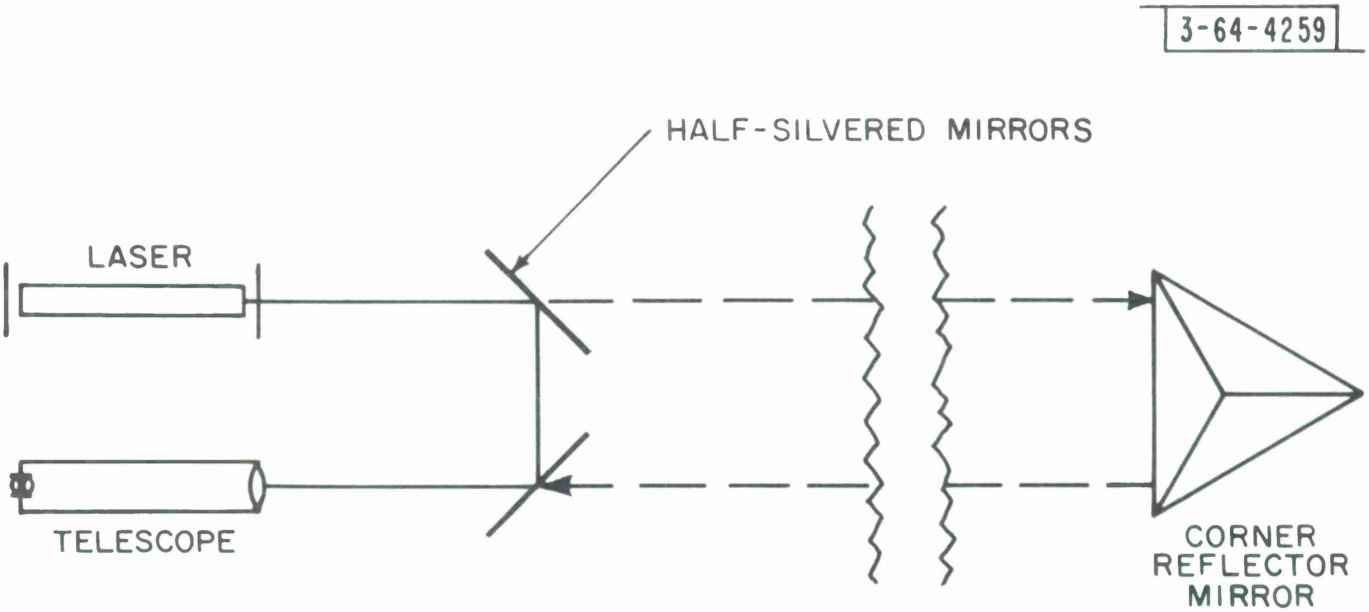
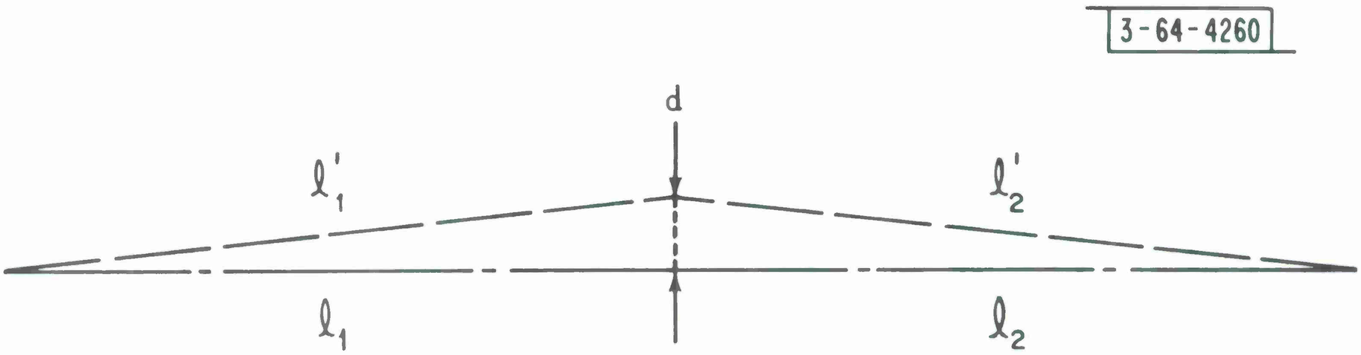


Fig. 2. Schematic of laser interferometer.



$$\ell_1' + \ell_2' = \ell_1 + \ell_2 + \frac{\lambda}{2}$$

Fig. 3. Definition of First Fresnel Zone.

DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified	2b. GROUP None
3. REPORT TITLE A Review of Long-Range Earth Strain Measurement Techniques for Providing Earthquake Warning		
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Technical Note		
5. AUTHOR(S) *(Last name, first name, initial)* Gehrels, Ernst		
6. REPORT DATE 13 December 1965	7a. TOTAL NO. OF PAGES 22	7b. NO. OF REFS 8
8a. CONTRACT OR GRANT NO. AF 19(628)-5167 b. PROJECT NO. ARPA Order 512 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TN 1965-62 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TDR-65-564	
10. AVAILABILITY/LIMITATION NOTICES None		
11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency, Department of Defense	

13. ABSTRACT

One of the most valuable tools for studying earthquakes and faults is earth strain or displacement measurements. Geologists are now looking for minute telltale displacements that might occur before an earthquake. This report discusses the possible accuracies that might be achieved by three different electromagnetic measurement techniques: 1) Microwave phase measurements, 2) Modulated light beam, and 3) Laser interferometers. The first is extremely sensitive to propagation errors. The second can achieve a modest degree of accuracy, 10^{-7} or better, and will clearly meet the minimum requirements. The third will provide by far the greatest degree of accuracy for propagation path lengths over which at least a partial degree of coherence of the wave front can be maintained.

14. KEY WORDS

earthquakes
strain measurements
microwave phase measurements
modulated light beams
laser interferometers